Self-Aligned-Gate GaN-HEMTs with Heavily-Doped n^+-GaN Ohmic Contacts to 2DEG

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Abstract

We report record DC and RF performance obtained in deeply-scaled self-aligned-gate GaN-HEMTs with heavily-doped n^+-GaN ohmic contacts to two-dimensional electron-gas (2DEG). High density-of-states of three-dimensional (3D) n^+-GaN source near the gate mitigates ñsource-starvation,ò resulting in a dramatic increase in a maximum drain current (I_{dmax}) and a transconductance (g_m). 20-nm-gate D-mode HEMTs with a 40-nm gate-source (and gate-drain) distance exhibited a record-low R_{on} of 0.23 Ω·mm, a record-high I_{dmax} of >4 A/mm, and a broad g_m curve of >1 S/mm over a wide range of I_{ds} from 0.5 to 3.5 A/mm. Furthermore, 20-nm-gate E-mode HEMTs with an increased L_{sw} of 70 nm demonstrated a simultaneous f_T/f_{max} of 342/518 GHz with an off-state breakdown voltage of 14V.

Introduction

Deeply-scaled E/D-mode GaN-HEMTs with an unprecedented combination of high-frequency and high-breakdown characteristics offer practical advantages in circuit applications such as sub-millimeter-wave power amplifiers, ultra-linear mixers, and increased output power digital-to-analog converters. During the last few years, through innovative device scaling technologies GaN-HEMT cutoff frequencies have been significantly increased - almost doubled - while maintaining Johnson figure of merit (*JFoM*) breakdown performance [1]. It is reported that in deeply-scaled FETs highly-doped source/drain (S/D) can significantly improve device performance by enhancing electron supply in the source [2,3]. Regrown n^+-GaN ohmic contacts have been shown to be one of viable technologies to reduce parasitic access resistances [4,5]. However, much attention has not been paid to an important role of heavily-doped S/D contacts in mitigating ñsource-starvationò which limits present GaN-HEMT performance. In this paper, we, for the first time, have developed self-aligned-gate GaN-HEMTs with regrown n^+-GaN S/D in direct contact with the 2DEG near the gate, and demonstrate dramatically enhanced DC and RF characteristics in conjunction with engineering of the lateral device dimensions.

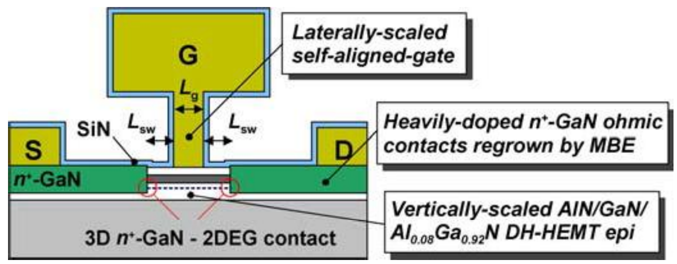

Fig. 1. Deeply-scaled self-aligned-gate double-heterojunction (DH) HEMT with heavily-doped regrown n^+-GaN ohmic contacts to the 2DEG in the GaN channel.

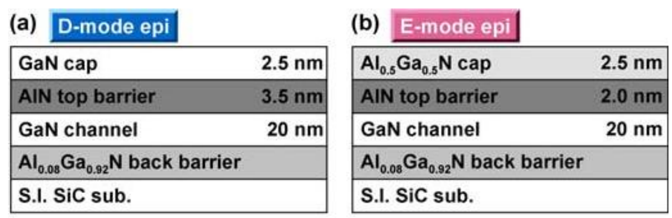

Fig. 2. Vertically-scaled (a) D-mode and (b) E-mode DH-HEMT epitaxial structures.

Device design

Fig. 1 illustrates a technology cross-section featuring (i) a laterally-scaled self-aligned-gate, (ii) vertically-scaled depletion and enhancement-mode AlN/GaN/AlGaN double-heterojunction (DH) HEMT epitaxial structures as detailed in Fig. 2, and (iii) heavily-doped n^+-GaN ohmic contacts regrown by MBE. A high 2DEG density (n_s) of $1.2(D)/1.1(E)\times10^{13}\,cm^{-2}$ and a high electron mobility (μ) of 1200(D)/1250(E) $cm^2/V{\cdot}s$ were measured after surface passivation with SiN. Heavily-Si-doped n^+-GaN ohmic layers ($7\times10^{19}\,cm^{-3}$, 50 nm) laterally contact to 2DEG in the GaN channel. A Pt/Au gate is then self-aligned to the n^+-GaN ohmic contacts using a dielectric sidewall process by which gate-source and gate-drain distances are determined by the sidewall thickness (L_{sw}). Fig. 3 compares two regrown n^+-GaN ohmic structures; (a) A regrown n^+-GaN ohmic layer directly contacts to the 2DEG, where electrons are supplied from the 3D n^+-GaN source to the 2DEG channel near the gate (3D-2D). (b) An n^+-GaN ohmic layer was regrown on top of the (Al)GaN/AlN barrier layers as reported in our previous paper [1], where electron are

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14. ABSTRACT
We report record DC and RF performance obtained in deeply-scaled self-aligned-gate GaN-HEMTs with heavilydoped n+-GaN ohmic contacts to two-dimensional electrongas (2DEG). High density-of-states of three-dimensional (3D) n+-GaN source near the gate mitigates source-starvation, resulting in a dramatic increase in a maximum drain current (Idmax) and a transconductance (gm). 20-nm-gate D-mode HEMTs with a 40-nm gate-source (and gate-drain) distance exhibited a record-low Ron of 0.23 ·mm, a record-high Idmax of >4 A/mm, and a broad gm curve of >1 S/mm over a wide range of Ids from 0.5 to 3.5 A/mm. Furthermore, 20-nm-gate E-mode HEMTs with an increased Lsw of 70 nm demonstrated a simultaneous fT/fmax of 342/518 GHz with an off-state breakdown voltage of 14V.

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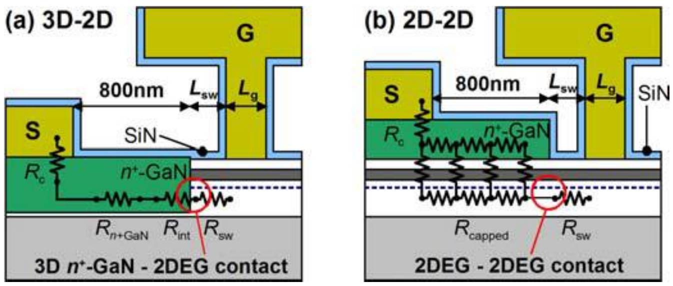

Fig. 3. Comparison of two regrown n^+-GaN ohmic structures; (a) a new 3D n^+-GaN source to 2DEG channel contact (3D-2D), and (b) 2DEG source to 2DEG channel contact (2D-2D) in our previous paper [1].

supplied from the 2DEG source to the 2DEG channel (2D-2D).

Results and Discussion

An access resistance (R_{ac}), defined as a total resistance from the ohmic metal to the edge of the gate, of 0.101 Ω·mm is the lowest value ever reported in GaN-HEMTs (Fig. 4). Resistance components of R_{ac} are shown in Fig. 4, which were extracted from a TLM test structure, contactless sheet resistance measurement, and dependence of device on-resistance (R_{on}) on L_g (Fig. 5). The regrown interface resistance (R_{int}) between the n^+-GaN and the 2DEG is only 0.026 Ω·mm, reaching its theoretical limit [$\sim h/(2q^2 \cdot n_s^{1/2}) = 0.036$ Ω·mm] [6]. More importantly, this new approach not only reduces R_{ac} but also increases flexibility in a material choice of GaN-HEMT epi structures since the R_{ac} is independent of the barrier materials as is the case for the conventional approach. Fig. 6 and Fig. 7 compare DC characteristics of 60-nm D and E-mode HEMTs with 3D-2D and 2D-2D contacts. Reduced R_{on} by -18% (-19%) for D (E)-mode device is a result of the reduced R_{ac}. I_{dmax} is dramatically increased by +34% (+45%) for D (E)-mode device due to an increase of g_m at high I_{ds}. This result clearly illustrates that typical g_m roll-off at high I_{ds} observed in previous devices is due to the limited electron supply from the source, i.e., ñsource-starvation.ò 20-nm-gate D-mode HEMTs with L_{sw} = 40 nm exhibited a record-low R_{on} of 0.23 Ω·mm, a record-high I_{dmax} of >4 A/mm, and a broad g_m curve of >1 S/mm over a wide range of I_{ds} from 0.5 to 3.5 A/mm (Fig. 8). Fig. 9 shows a peak g_m of E-mode HEMTs as a function of L_g for various L_{sw}, indicating that the closer the n^+-GaN/2DEG interface is to the gate, the more efficiently electron are supplied from the 3D n^+-GaN source. The record-high g_m of 2.2 S/mm was measured for a device with L_g/L_{sw} = 40/50 nm.

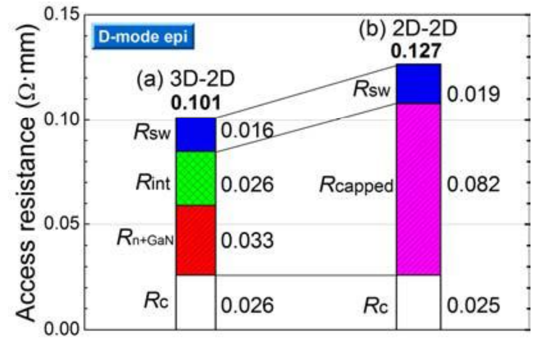

Fig. 4. Access resistance (R_{ac}) components for two regrown n^+-GaN ohmic structures shown in Fig. 3. An extremely small R_{ac} of the new 3D-2D structure resulted from ideal regrown interface resistance (R_{int}) that reaches the theoretical limit.

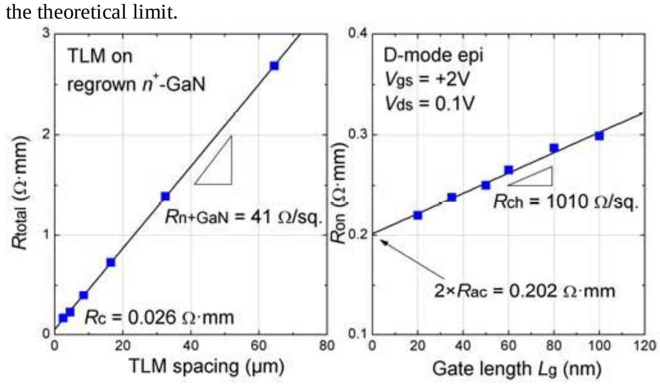

Fig. 5. Extraction of access resistance (R_{ac}) components shown in Fig. 4 using a TLM on a regrown n^+-GaN and dependence of R_{on} on L_g.

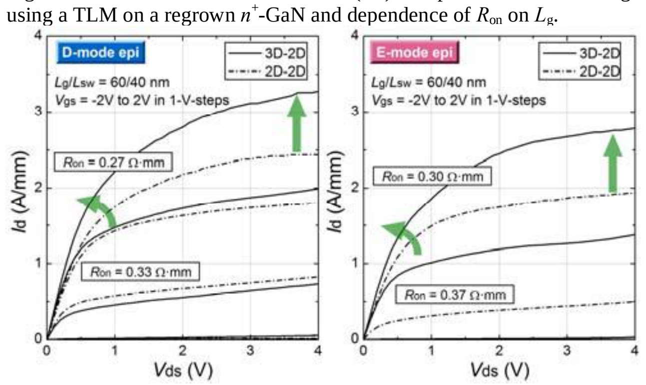

Fig. 6. Output characteristics of 60-nm D and E-mode HEMTs (L_w = 40 nm) with 3D-2D and 2D-2D contacts, demonstrating a reduction of R_{on} and a dramatic increase of I_{dmax} using 3D n^+-GaN source.

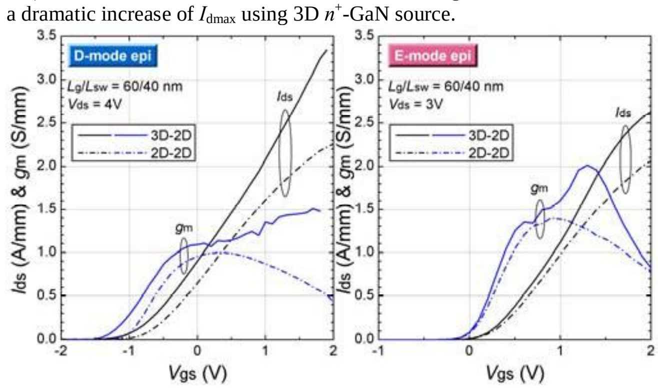

Fig. 7. Transfer characteristics of 60-nm D and E-mode HEMTs (L_w = 40 nm) with 3D-2D and 2D-2D contacts, demonstrating suppressed g_m roll-off at high I_{ds} due to enhanced electron supply by 3D-2D contact.

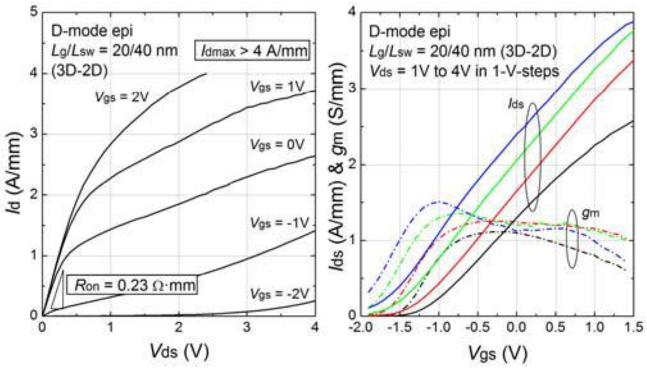

Fig. 8. Output and transfer characteristics of a 20-nm D-mode HEMT (L_{sw} = 40nm) with a 3D-2D contact, showing a record-low R_{on} and a record-high I_{dmax} with very broad g_m curves.

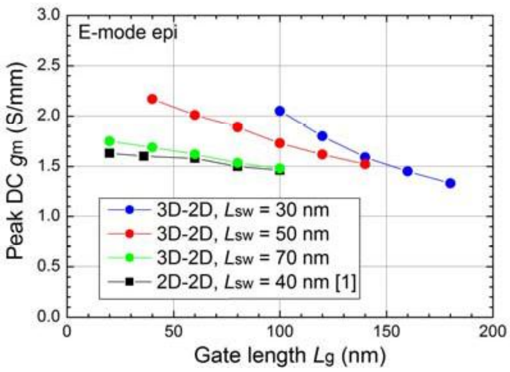

Fig. 9. Peak DC g_m of E-mode HEMTs as a function of L_g for various L_{sw}, indicating enhanced electron supply with reduced L_{sw}.

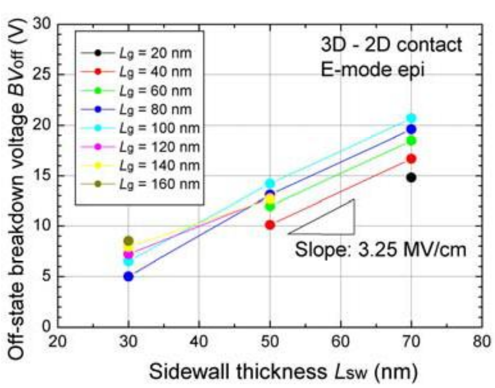

Fig. 10. Off-state breakdown voltage (BV_{off}) of E-mode HEMTs linearly increases with L_{sw} with a slope of 3.25 MV/cm.

While the shorter gate-source distance (L_{gs}) enhances the electron supply, the longer gate-drain distance (L_{gd}) increases breakdown voltage and reduces output conductance (g_d) and gate-drain capacitance (C_{gd}). Off-state breakdown voltage (BV_{off}) increased linearly with increasing L_{sw} with a slope of 3.25 MV/cm, close to the critical field of GaN (~3.4 MV/cm) (Fig. 10). Drain induced barrier lowering (*DIBL*) for sub-50-nm gate lengths (L_g) improved significantly with increasing L_{sw} owing to an increased gate to drain electrostatic isolation (Fig. 11), leading to a lower g_d due to suppression of the

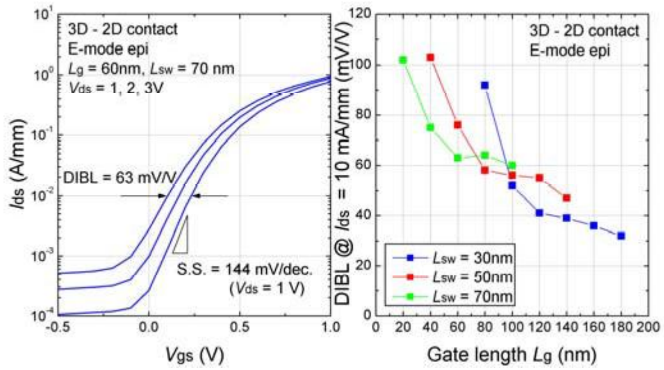

Fig. 11. Sub-threshold characteristics of an E-mode HEMT with L_g/L_{sw} = 60/70 nm. Dependence of *DIBL* on L_g for various L_{sw} shows an improved gate to drain electrostatic isolation with increased L_{sw}.

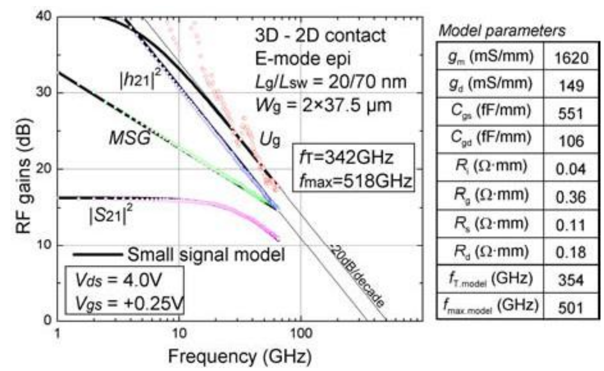

Fig. 12. The best combination of f_T/f_{max}=342/518GHz was achieved in a HEMT with L_g/L_{sw} = 20/70 nm. This record-high f_{max} is attributed to a reduced g_d and C_{gd} while maintaining a high g_m.

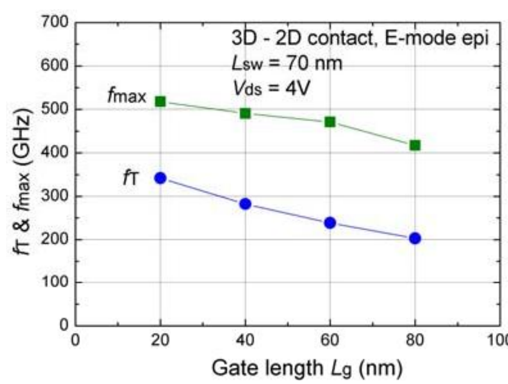

Fig. 13. Peak f_T/f_{max} vs. L_g showing high L_g scalability down to 20 nm.

ñshort-channel-effect.ò A balanced device design with L_g/L_{sw} = 20/70 nm in the E-mode HEMTs resulted in a simultaneous f_T/f_{max}=342/518GHz with a BV_{off} of 14V. This record-high f_{max} is attributed to the decreased g_d and C_{gd} due to the increased gate-drain distance together with a high g_m enabled by the new 3D n^+-GaN source contact to the 2DEG (Fig. 12). Fig. 13 shows good scaling behavior of f_T/f_{max} with L_g down to 20 nm. As a result of proportional device scaling and enhanced electron supply in self-aligned-gate

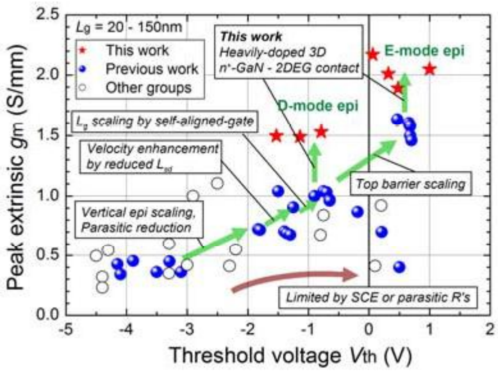

Fig. 14. Comparison of extrinsic peak g_m vs. V_{th} with the state-of-the-art results reported for GaN-HEMT technology.

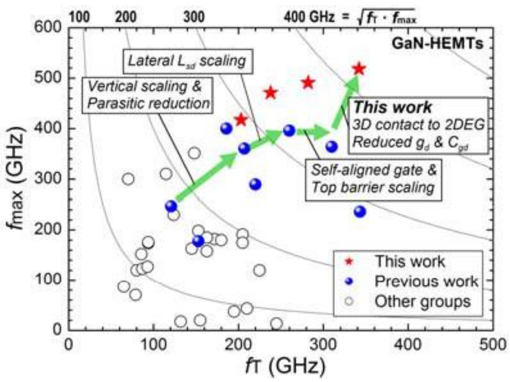

Fig. 15. Proportional device scaling and enhanced electron supply in deeply-scaled self-aligned-gate GaN-HEMTs successfully resulted in a record f_T and f_{max} exceeding an average cutoff frequency of 400 GHz.

GaN-HEMTs, enhanced peak g_m in excess of 2 S/mm (Fig. 14) and an average cutoff frequency [= $(f_T \cdot f_{max})^{1/2}$] of >400GHz were obtained (Fig. 15).

Conclusion

Heavily-doped n^+-GaN S/D contacts to the 2DEG in deeply-scaled self-aligned-gate GaN-HEMTs were demonstrated for the first time. The new technology was shown to effectively mitigate ñsource-starvation,ò resulting in a significant enhancement in R_{on}, I_{dmax}, g_m, and g_m linearity. An R_{on} of 0.23 Ω·mm, an I_{dmax} of >4 A/mm with a broad g_m curve of >1 S/mm over a wide range of V_{gs} was obtained in 20-nm D-mode HEMTs with L_{sw} = 40 nm. In conjunction with lateral device size optimization for a reduced g_d and C_{gd} as well as an increased BV_{off}, a record f_T/f_{max} of 342/518 GHz was obtained in 20-nm HEMTs with a $JFoM$ of 4.8 THz·V.

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